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Effects of Processing Conditions on Vacuum Assisted Resin Transfer Molding Process (VARTM)

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Abstract

The continued growth of vacuum-based processes has warranted the development of both models and experimental studies designed to capture the unique aspects associated with this manufacturing technique. To that end, this report summarizes an initial set of experiments that characterize both the process and the resulting mechanical properties of components fabricated under a variety of process conditions. Specifically, resin flow studies are presented in part to demonstrate the relative influence of key parameters on the flow front developed during impregnation. The effect of the distribution medium, which is used in a commercial version of VARTM known as Seeman's Composite Resin Infusion Molding Process (SCRIMP), is explicitly characterized. In addition, the variation of part thickness is also examined, and potential mechanisms responsible for these variations are presented. A battery of mechanical tests designed to correlate the effect of various processing conditions are also presented. A major finding is that thickness variation can be significant and, to some degree, random; also, precompaction of the preform significantly influences the amount of consolidation pressure needed during impregnation. Dimensional variations due to gradients in the pressure distribution of the vacuum affect permeability (and hence resin flow), as well as dimensional tolerances in manufactured parts.

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Contents

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List of Figures

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List of Tables

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1. Introduction

The benefits of vacuum assisted resin transfer molding (VARTM) are well known for certain applications (e.g., large hull structures, structural members, and transport compartments). These benefits include low volatile emissions, reduced tooling costs, and decreased cycle times associated with the process [1–2]. There is, however, the potential for the lack of part-to-part consistency, and the overall part quality may not be equal to conventional prepreg materials. Recent work has been published on the effects of fiber compaction on the quality/mechanical properties of composite materials processed with VARTM [3–10]. The lower fiber volume fraction (V_f) associated with a low-pressure molding process may not be a problem for relatively thin section, nonstructural/nonballistic applications, but for areas where thick section composites are needed, further research into process optimization must be performed. If high fiber volume, thick-section composites can be manufactured by a low cost VARTM process or by a modified VARTM process, the increased use of these materials will be seen in a variety of vehicle and structural applications.

In less than a decade, a major shift has occurred in the processing of large, relatively complex fiber-reinforced structures. This shift is centered primarily around the adoption of purely vacuum based processes and the migration to one-sided, inexpensive tooling. These processes are generally known as VARTM and include a number of patented and commercialized processes such as SCRIMP [9].

The principal advantage of the VARTM class of processes is the inherent cost-effectiveness associated with its implementation. Processing costs alone constitute between 50 and 60% of the typical end item cost; thus, there is significant incentive to continually explore new processes that can affordably provide the desired properties. A typical VARTM process is illustrated in Figure 1, where a preform is laid up onto a one-sided tool. The preform may already be stitched, or successive layers can be stacked up until the desired part thickness is achieved. Next, a series of feed tubes is placed around the structure to enable a continuous supply of resin to the part. In the case of SCRIMP [9], a patented and commercialized process, a layer of distribution medium is also inserted. In effect, the distribution medium is a highly permeable material that allows the resin to flow through a fiber preform with greater ease. A vacuum bag is subsequently fitted over all of the aforementioned materials and fixtures. It is not uncommon to use a second vacuum bag to minimize variations in compaction pressure and guard against potential vacuum leaks in the primary vacuum bag.

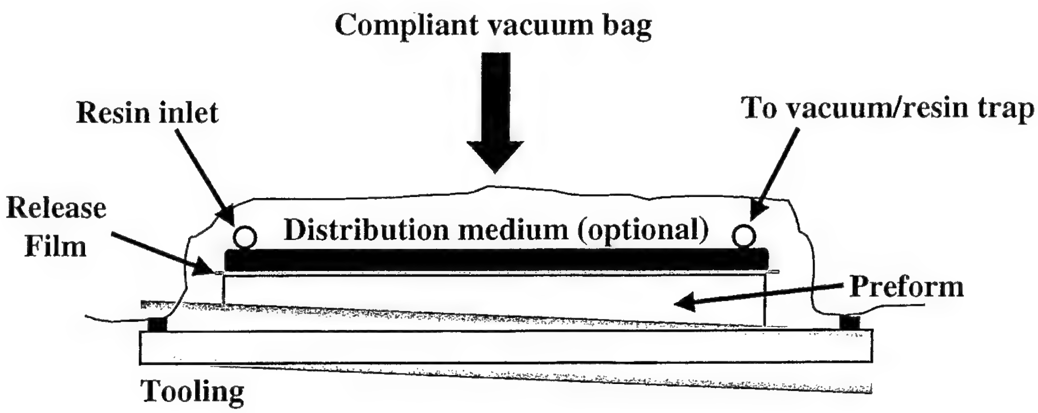

Figure 1. Typical VARTM process.

Once the process is properly configured, resin is supplied at atmospheric pressure. The pressure differential arising from the resin source at atmospheric pressure, along with the evacuated preform, stimulates resin impregnation of the fibrous preforms. Although this process appears to be quite simple, a number of disadvantages exist in the current practice of VARTM processing, and relatively little is understood about the coupled nature of the resin flow and preform consolidation [11, 12].

2. Motivation for Present Research

As the resin flow front moves away from its source, its velocity decreases in accordance with Darcy's law. Only recently have models appeared describing the unique behavior of the resin flow front in the presence of a vacuum. The industrial practice of VARTM has thus relied on trial and error to determine near optimal operating parameters and process configurations. For example, the "rule of thumb" is to place successive line sources approximately 18 in apart for a vinyl ester resin in combination with a woven glass fabric. If the spacing is much greater than this, the flow front begins to stall so significantly that the total impregnation time can be doubled. Much of the success in VARTM has been achieved through trial and error; a more rigorous and fundamental understanding of the process is required to improve the process.

3. Experimental

3.1 Materials

The reinforcement material used in this study is an Owens Corning S-2 fiberglass, 24-oz/yd^2 woven roving, 5 × 5 plain weave fabric. The resin used is Applied Polymeric SC-15, a rubber toughened, low viscosity epoxy. Test laminates were 20 in × 20 in × 22 plies thick; they were infused with a resin feed line across one end and a vacuum line across the other end of the part. A release film was placed on top of the preform, and then the resin distribution medium along with vacuum and resin feed lines were installed and sealed under a vacuum bag.

3.2 Methods

Several approaches were taken to determine how a fiber preform compresses and fills. To determine theoretical maximum fiber nesting, the mechanical compressibility of dry and wet fiber preforms was conducted on an Instron load frame. Mechanical test specimens using different VARTM processing techniques, as well as one set cured in a mechanical press, were made to determine mechanical variations among different techniques. Variations in the infusion and bagging methods were investigated, as well as preform infusion time with and without a resin distribution medium. All infused parts were fabricated on a glass tabletop, as shown in Figure 2, where both top and bottom infusion times could be determined.

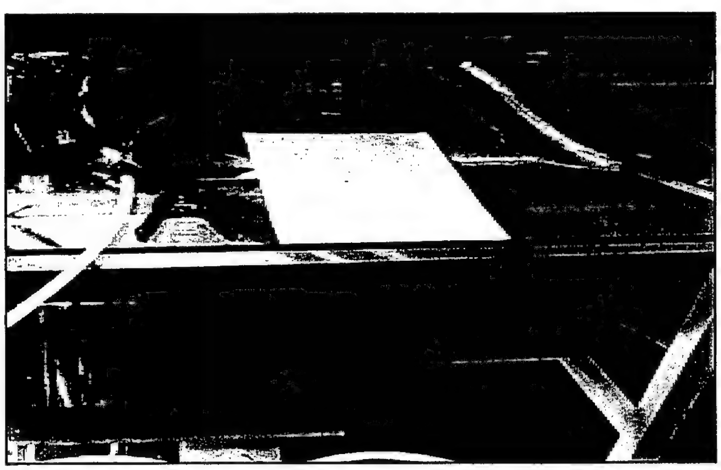

Figure 2. Infusion on glass tabletop with mirror underneath to observe and record flow on bottom of preform.

3.3 Mechanical Compressibility of Fiber Preform

The fiber volume fractions (V_f) of glass preforms were estimated using an Instron 1145 mechanical load frame operated under load control. The crosshead displacement was determined using a linear variable displacement transducer. Load and displacement data were collected as a function of time. The crosshead displacement of the load frame was used to determine the thickness of the fiber pack, and it enabled the calculation of theoretical fiber volume fraction. Both dry- and resin-infused preforms were compressed under static and dynamic loads to determine the potential V_f of the composite plates manufactured under different processing conditions. In each test, nine plies of fiberglass fabric were subjected to different loading conditions. Nine ply specimens were fabricated for all the mechanical tests using the same processing conditions as the 22-ply preforms in the flow studies.

A series of tests were conducted to measure the V_f of a dry- and resin-infused composite preform under dynamic and static loads. The resin-infused composite preforms were cured between the platens of the mechanical load frame after cyclic loading to compare to parts made in a mechanical compression press.

3.4 Physical/Mechanical Properties

The physical and mechanical properties of the composite materials were determined according to ASTM standards. The fiber volume fraction of the composites was determined through ASTM D4963. The apparent interlaminar shear strength was determined by the ASTM D2344 short beam shear method, while the flexural modulus and flexural strength were determined by ASTM D790. The tensile modulus and tensile strength were determined by ASTM D638, and the interlaminar shear response was determined by ASTM D3518 in ±45° tension.

3.5 Resin Infusion Experiments

Variations in infusion times were monitored and recorded while infusing 22 plies of S2 glass, 24 oz/yd^2, 5 × 5 plain weave fabric. Relative to the preform, the height of the resin feed source was varied to determine the effects of gravity on total fill time. One set of preforms was infused with the resin feed source placed approximately 3 ft below the preform surface. A second set was infused with the resin feed source at the same height as the preform. A third set of panels was infused with the resin feed source placed at the same height as the preform, but a semi-rigid transparent thermoplastic sheet was added between the distribution medium and the vacuum bag. This was done to determine whether the rigid thermoplastic sheet would have an effect similar to a compression press with a rigid surface on both sides of the preform. Five panels were infused using each

method, and the averages are reported. All parts were infused using a single vacuum bag while incorporating a 50% shade distribution medium on top of the preform (shade refers to the approximate amount of light the distribution medium blocks out). After infusion, parts were cured using either single or double bagging techniques to evaluate how this affects the cured thickness.

Another set of experiments was conducted to provide both quantitative and qualitative assessments of the effect of using a distribution medium in the VARTM process. Using a highly porous distribution medium sandwiched between the preform and the vacuum bag is patent protected by Seeman [9]. A flow experiment was devised to reveal the relative effect of including a distribution medium. The general features of the experiment are shown in Figure 3.

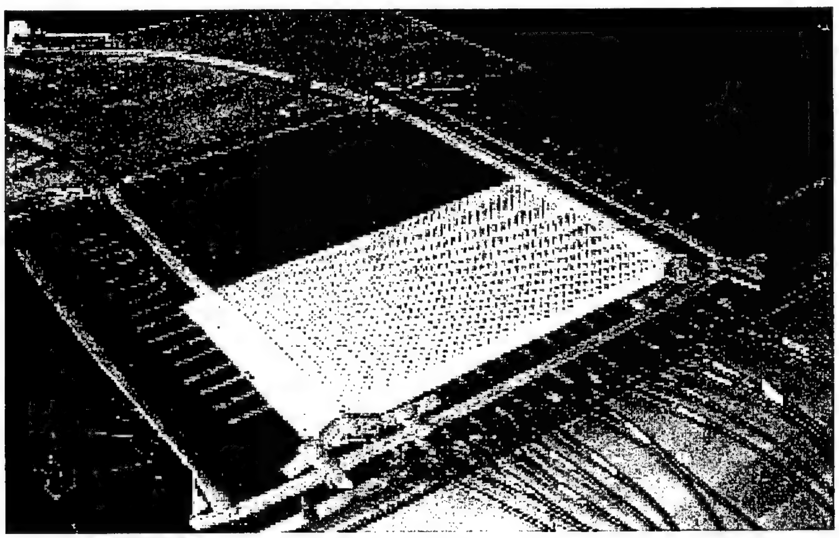

Figure 3. Laminate with distribution medium on left half.

As Figure 3 shows, a layer of distribution medium was applied to only one half of a six-ply woven S-2 glass preform. A uniform line source has been orthogonally located on one end; similarly, a vacuum outlet is located at the other. A layer of SMARTweave [13] was installed to capture the location of the flow front on the tool side; this is explicitly shown in Figure 4. In this particular apparatus, the tool side was 1/2-in-thick plate glass. Glass was selected not only to provide direct visualization of the flow front, but also to validate the utility of SMARTweave as a practical in-situ method for locating flow movement and rate. For this experiment, a resin simulant consisting of corn syrup and water was used; the viscosity of the simulant was adjusted to mimic that of a typical epoxy. The instantaneous location of the flow front was obtained by tracing the contours at 30-s intervals on the top and bottom layers of the glass, as shown in Figure 5.

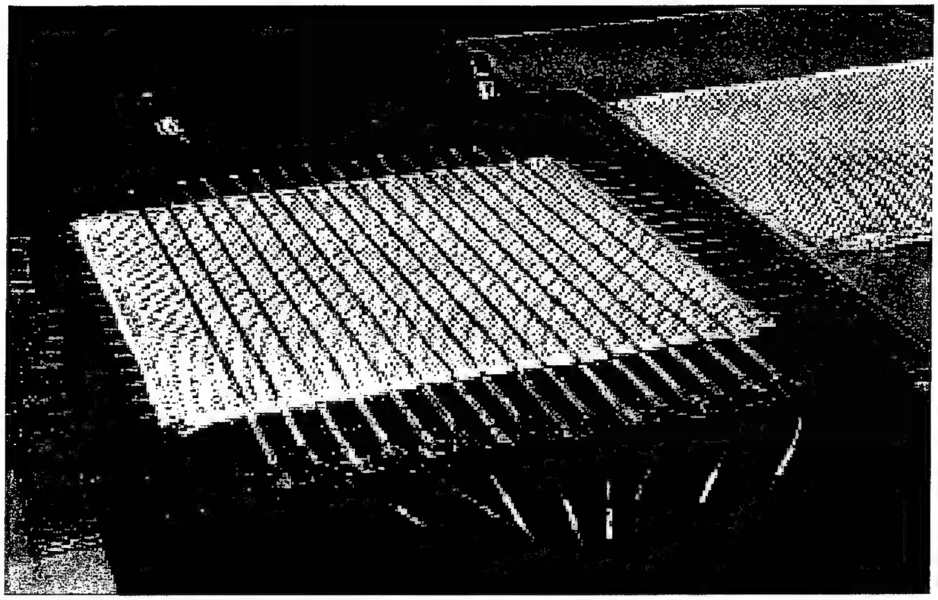

Figure 4. Installation of SMARTweave adjacent to tool (glass) surface.

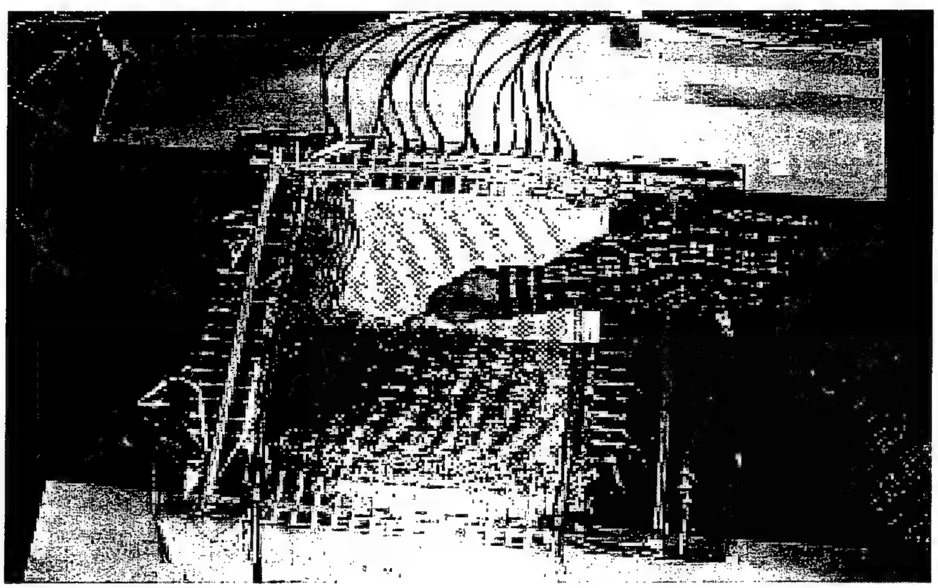

Figure 5. Manual tracing of flow fronts during impregnation.

4. Results and Discussion

4.1 Discussion of Flow Results

The effect of the distribution medium in infusing a preform was dramatic, as anticipated. The flow front traversed the distance from the line source to the vacuum line in less than 4 min on the side of the laminate containing the distribution medium. It took over 2 hr for the flow front to traverse the same distance on the side without the distribution medium. However, there are key points and differences to be noted in comparing these results. First, these time comparisons were made on the top layer. It took over 30 min for the flow to traverse the same distance on the bottom surface (beneath the half with the distribution medium). That is, there was a significant transfer flow gradient through the thickness of the part. In contrast, there was virtually no gradient in the side without the distribution medium (i.e., the flow front was near plug flow, proceeding at the same rate throughout the thickness of the laminate). In addition, the rapid arrival of resin at the vacuum on the side with the distribution medium appears to have resulted in a significant drop off in vacuum pressure, thus causing the flow to stall significantly on the side without the distribution medium. The effect of liquid prematurely reaching the vacuum was studied previously [14]. The location and nature of the vacuum can play a very significant role in flow front development during impregnation.

The flow front behavior on the tool surface of the side containing the distribution medium revealed other effects, as indicated by the contours shown in Figure 6. First, even though the flow progresses more rapidly on the surface below the distribution medium, the flow front itself was notably irregular. The flow appeared to stall and then "leap" ahead, as indicated by the peaks of the contour curves. This phenomenon occurred at least three times during the impregnation. This effect has been informally reported from various users of VARTM processing. Figure 6 conclusively reveals the behavior of the flow front on the otherwise inaccessible tool side. Given that a glass tool is not practical in an actual processing scenario, SMARTweave [13] is thus presented as a viable means for monitoring flow.

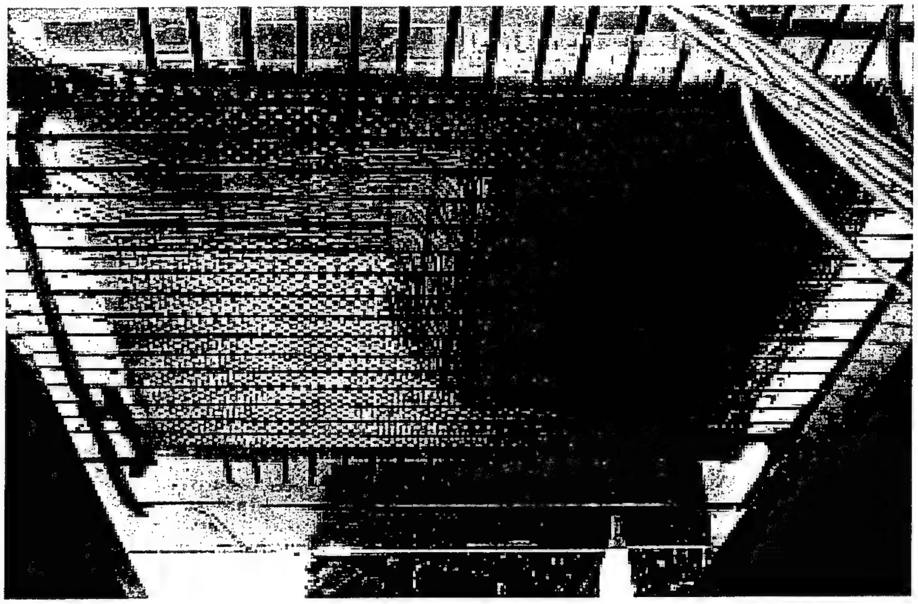

Figure 6. Bottom view of flow front contours on tool (glass) surface.

4.2 Discussion of Resin Infusion Results

Another set of experiments was conducted using a 22-ply preform with a distribution medium across the entire top layer. A rubber-toughened epoxy was used for these experiments. Average resin flow front times in seconds, across the surface of the part, for three different infusion methods are studied. The first method involved feeding the part with the resin feed source placed on the floor approximately 3 ft below the preform surface. The second method had the resin feed source elevated to the same height as the preform. The third method had the resin feed source placed at the same height as the preform, but with a semi-rigid transparent thermoplastic sheet added over the distribution medium but under the vacuum bag. All preforms were 20 in $\times$ 20 in with the distribution medium 18 in $\times$ 18 in. Figure 7 shows the average infusion times across the top layer for each method as a function of distance traveled. Figure 8 shows the corresponding average infusion times for the flow fronts across the bottom layer for each method.

As a function of distance from the vacuum source, variations in final part thickness were measured after the parts were fully cured. The elevated and elevated with plexiglas flow experiments were cured with a double bag after they were fully infused. This was done to gauge if a second vacuum bag affected part thickness. The final cured thickness of a part decreases as the vacuum source is approached, as shown in Figure 9. It should be noted that these averages are taken from parts manufactured using a line feed source on one end and a line vacuum source on the other end.

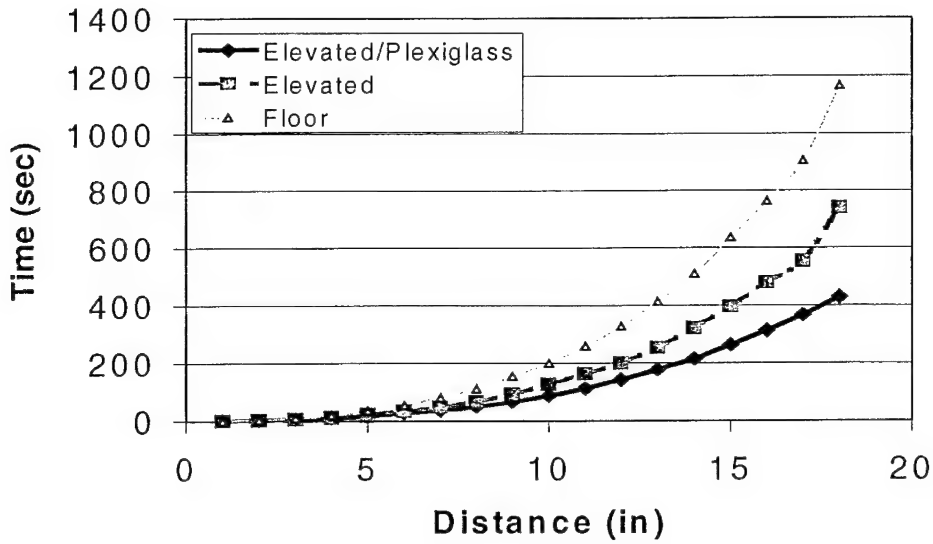

Figure 7. Infusion time across top of preform surface.

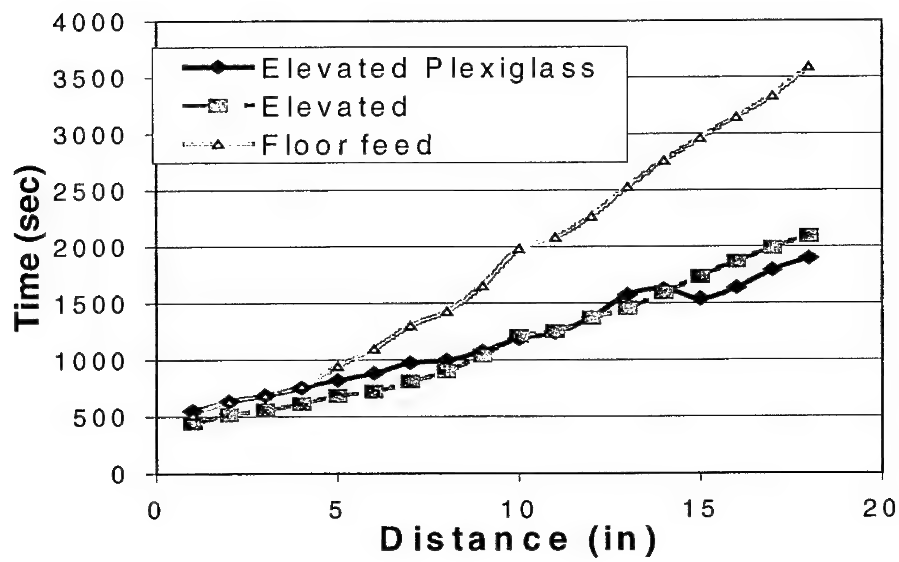

Figure 8. Infusion time across bottom of preform surface.

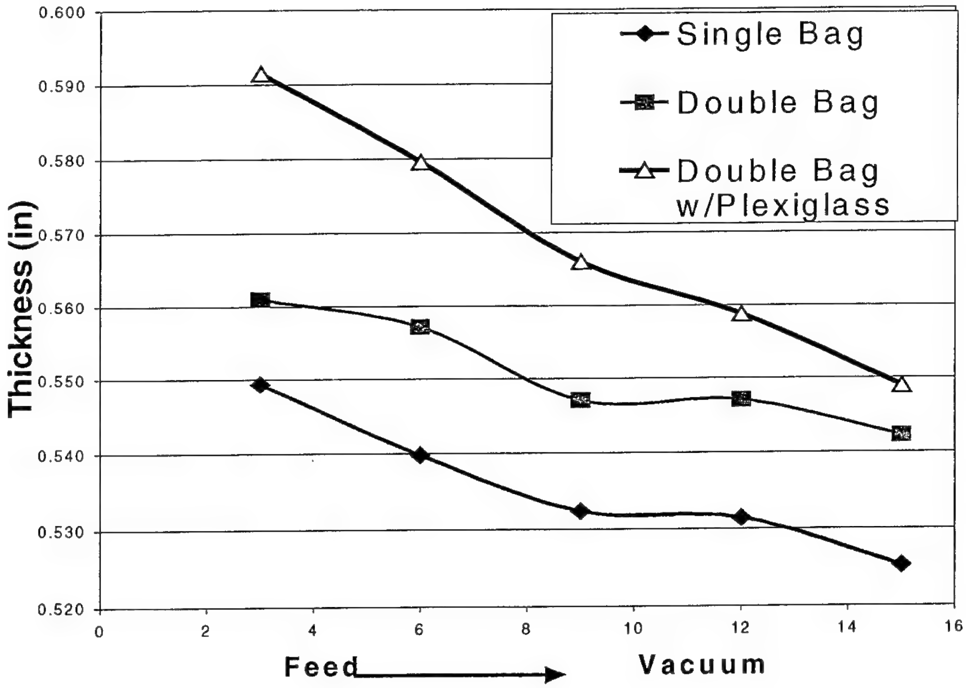

Figure 9. Cured part thickness vs. distance relative to vacuum source.

As a consequence of part to part thickness variations, there is a corresponding variation in the fiber volume fraction of the final part. As the distance from the vacuum source increases, the fiber volume fraction of the laminates decreases; this phenomenon is apparent in Figure 10.

4.3 Material Properties/Compressibility

Several experiments were also performed on the compressibility of the fiberglass preforms to determine the effects of pressure on the V_f. Dry fiberglass preforms were loaded from 0 to 6 atm in the first series of tests. Figures 11 and 12 illustrate the effect of pressure on 43 and 9 plies of glass fabric, respectively. The 43-ply sample has the lowest initial V_f of 50%, and the 9-ply preform has a higher initial V_f of 55%. Since perfect fiber bundle nesting does not occur in practice, the thicker the preform the higher the potential for part to part variations due to an increase of free volume in every additional layer of reinforcement. By mechanically loading and unloading the preform, a maximum V_f may be attained prior to applying vacuum pressure for resin infusion. This, however, may adversely affect the resin permeability.

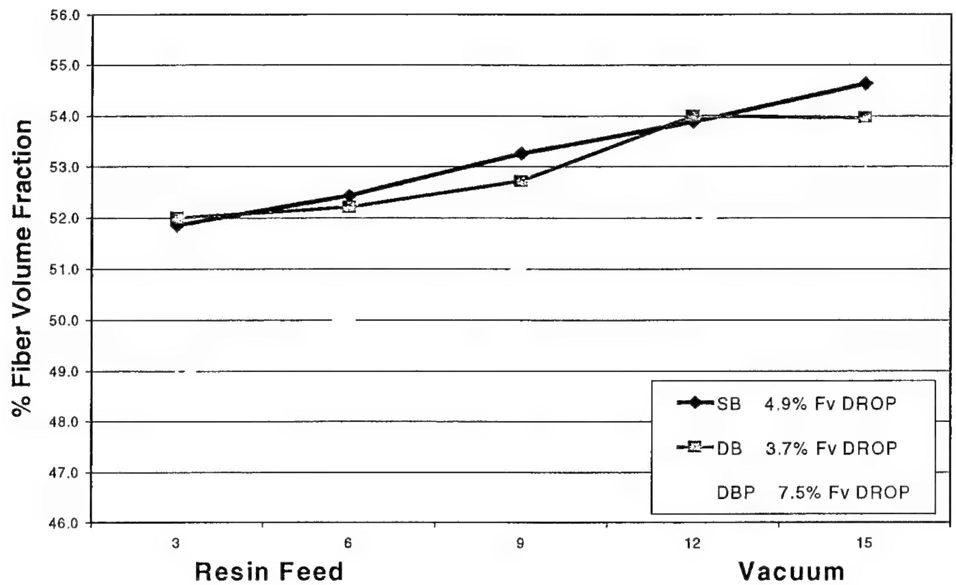

Figure 10. Graph of fiber volume fraction change vs. distance relative to vacuum.

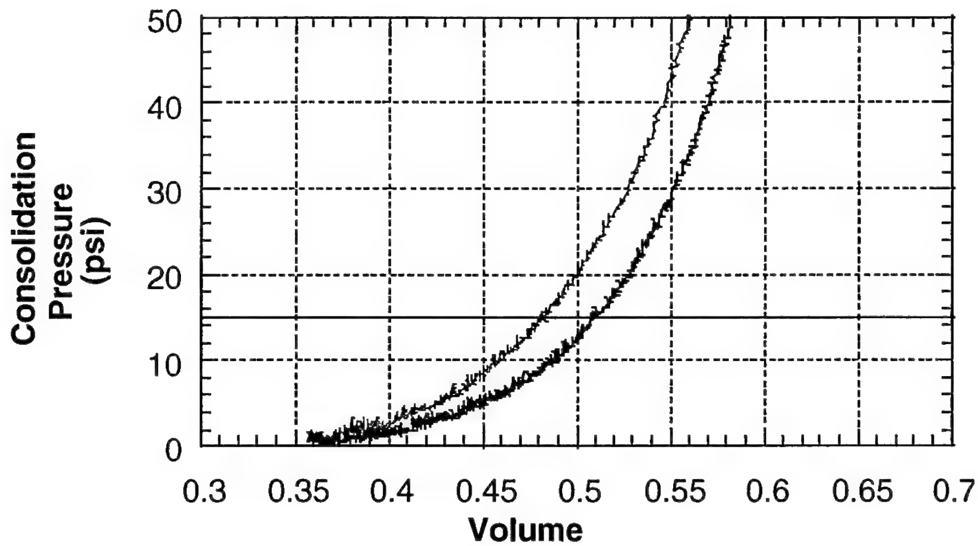

Figure 11. Compressibility curves for 43 plies of fiberglass fabric loaded twice from 0 to 90 psi (full scale not shown).

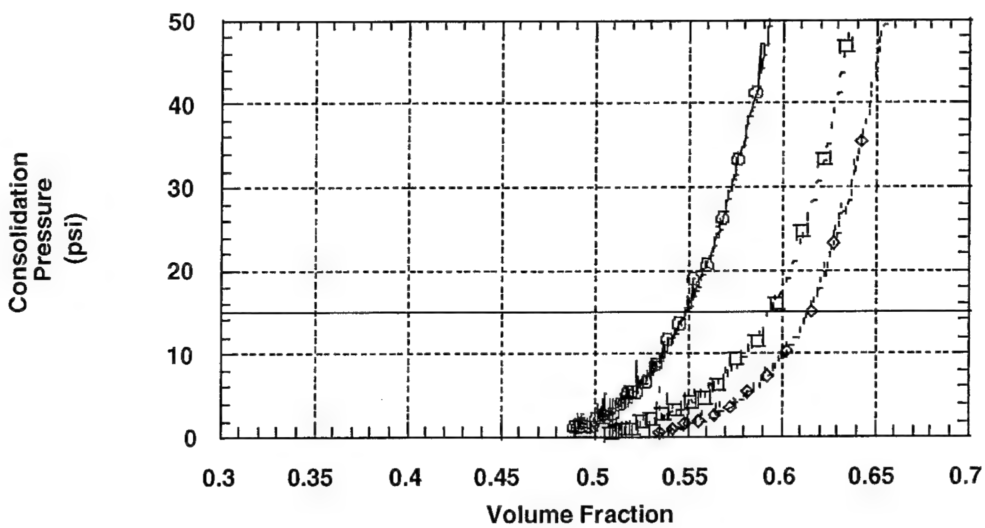

Figure 12. Compressibility curves for nine plies of fiberglass fabric loaded three times from 0 to 90 psi (full scale not shown).

Another series of tests was performed to simulate the effects of low vacuum pressure on the compressibility of a fiberglass preform. A load was applied to the dry laminate and held for approximately 30 min, as shown in Figure 13. This load is equal to 0.33 atm of pressure and would simulate consolidation and infusion under poor vacuum conditions or a broken vacuum bag scenario. The maximum V_f achieved under these conditions was approximately 46%.

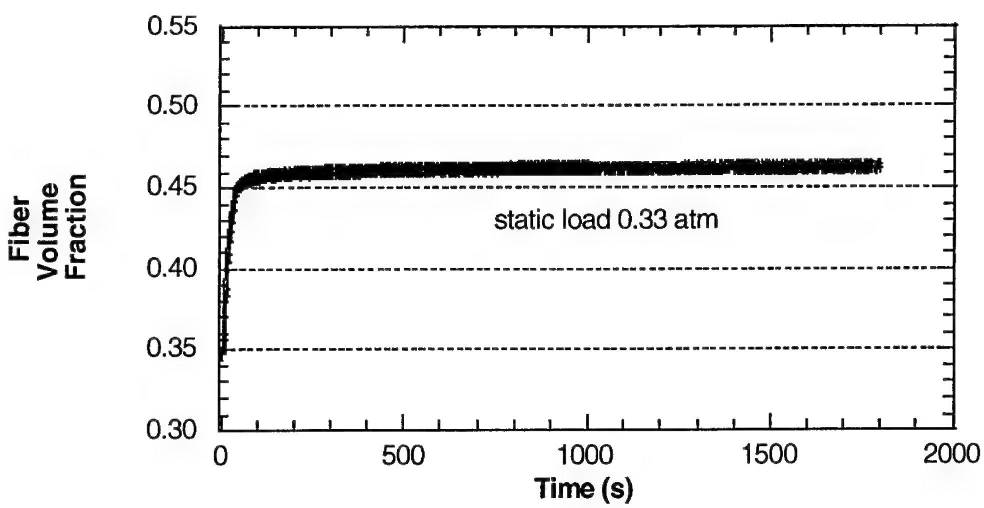

Figure 13. Compressibility curves for nine plies of fiberglass fabric loaded from 0 atm to 0.33 atm (0–5 psi).

In Figure 14, a load was applied to a dry laminate and held for approximately 30 min. This is equal to 1 atm of pressure and would simulate ideal vacuum conditions. The maximum V_f achieved was approximately 49%. The preform was then unloaded and reloaded to 1 atm, where the predicted V_f reached a value of 53%.

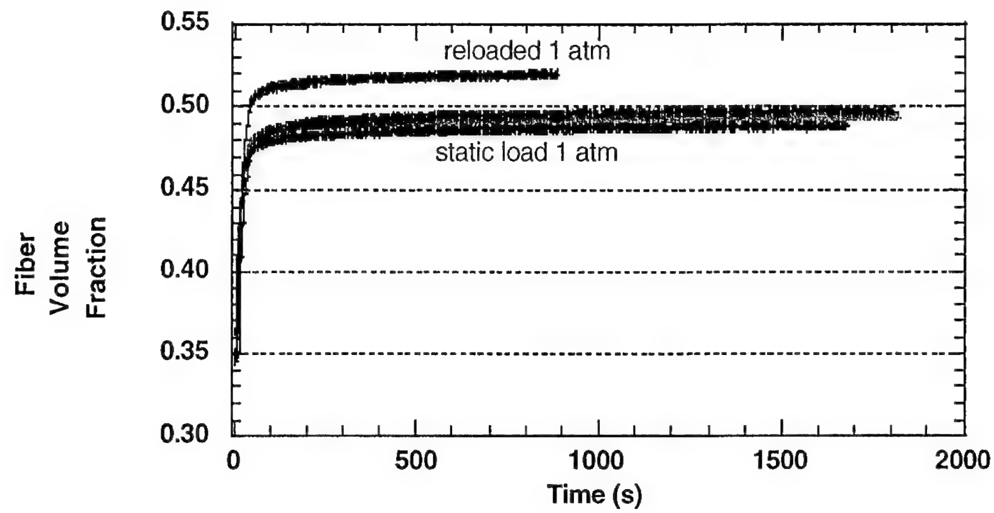

Figure 14. Compressibility curves for nine plies of fiberglass fabric loaded from 0 atm to 1 atm (0–15 psi). Top curve loaded twice from 0 atm to 1 atm (0–15 psi), which resulted in a higher fiber volume fraction.

Static and dynamic loads were applied to fiberglass preforms to evaluate the effect of loading on V_f. In Figure 15, a static load of 1-atm pressure was applied to the preform and held. A dynamic load, which cycled from 0.33 atm to 1 atm, was also applied to a nine-ply preform. This simulates the process of applying and releasing vacuum pressure during the bagging portion of a typical VARTM layup.

The data shows a small increase in the V_f of the dynamically loaded preform. This may account for some final part to part variations observed after processing since the vacuum pressure and how it has been applied may not always be the same from one VARTM run to the next. It may also be a useful parameter/design tool in producing higher V_f parts with reproducible properties. Although there is some elastic recovery, or spring back, of the fiberglass preform associated with reducing the pressure, it is not fully reversible within the given time frame. When the vacuum pressure is reduced from 1 to 0.33 atm in this experiment, the V_f is higher than the maximum V_f attained under statically loading the preform to 0.33 atm.

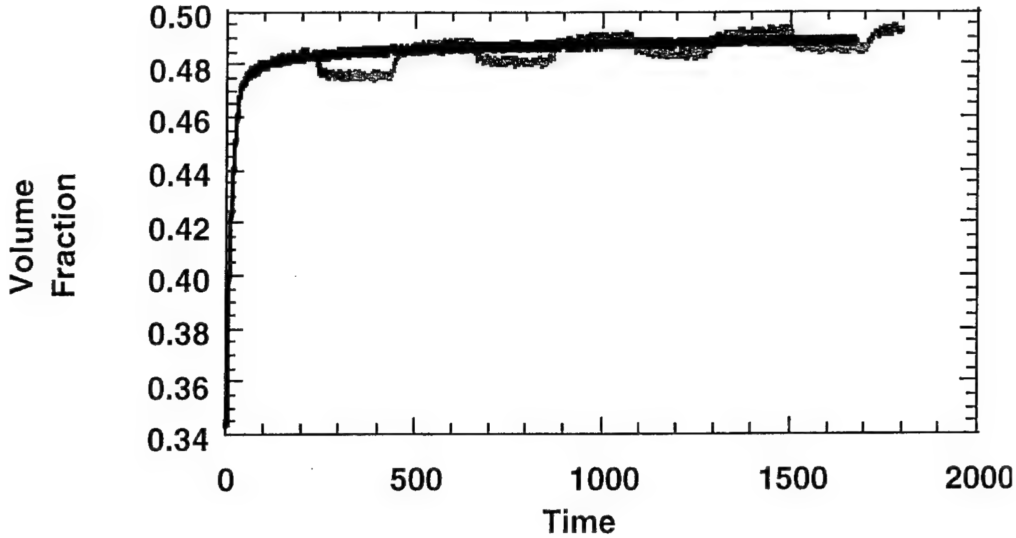

Figure 15. Comparison of static (15 psi) and dynamic (5–15 psi) loading on a fiberglass preform.

An additional dynamic loading experiment was performed to determine the lubrication effect of resin on the compressibility of a fiberglass preform. A nine-ply preform was infused with resin and loaded dynamically from 0.33 to 1 atm, as shown in Figure 16. This resulted in a theoretical V_f of 58% based on the cross-head displacement, which was a 16% increase over the dry fabric loaded in the same manner. This clearly illustrates the lubrication effect of the resin during any composites processing scheme.

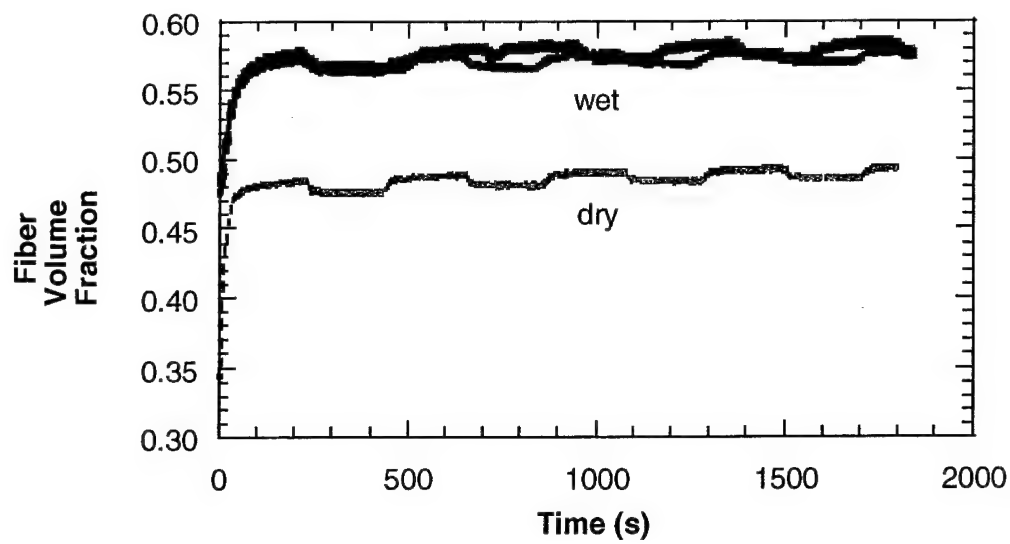

Figure 16. Comparison of wet and dry fiberglass preforms under dynamic loading (5–15 psi).

4.4 Physical and Mechanical Properties

The theoretical V_f values from the compressibility studies are compiled in Table 1. Not only can the V_f be changed by increasing the consolidation pressure, but also by applying a cyclic load or lubricating the fibers.

Table 1. Predicted fiber volume fractions of wet and dry fiberglass preforms compressed in an Instron mechanical test frame.

Wet/Dry	No. of Plies	Pressure (atm)	No. of Cycles	V_f at 1 atm
dry	43	0–6	2	51
dry	9	0–6	3	62
dry	9	0.33	1	47
dry	9	1	1	50
dry	9	1	2	52
dry	9	0.33–1	6	50
wet	9	0.33–1	6	59

The actual fiber volume fractions (V_f) of the composite laminates produced under different conditions are listed in Table 2. However, all of the values do not correspond to the predicted theoretical values based on the Instron data. The V_f value of 60.14% attained in the mechanical press and the 60.65% attained from the cured Instron samples correlate with the 59% V_f predicted with the wet preform compressed in the Instron. The V_f values calculated from the single- and double-bag VARTM do not correspond to the predicted values of preforms loaded under 1 atm of pressure. This may be attributed to poor vacuum pressure during processing. Or, it may be due to the inability of the process to remove excess resin after complete wet out, resulting in a lower V_f.

Table 2. Fiber volume fractions of composite parts processed under different conditions.

Resin Infusion Method	No. of Plies	Fiber Volume Fraction (%)
Single-Bag VARTM	8	51.13
Double-Bag VARTM	8	49.93
Mechanical Press VARTM	8	60.14
Instron Samples	9	60.65

The mechanical properties are presented in Table 3; they have been normalized to a V_f of 60%. The properties are consistent from one process to another as well as published manufacturer data [15]. The only obvious difference between the press and the VARTM processes is the variation in thickness and the V_f. The laminates processed between the platens of a mechanical press or in the Instron had a lower part thickness and higher V_f when compared to the VARTM laminates.

Table 3. Mechanical properties of composite materials processed under different conditions.

Processing Method	ASTM Test Method	Mechanical Press	Single Bag VARTM
Fiber Volume Fraction	D 4693	60.14	51.13
Apparent Shear Strength (ksi) CV	D 2344	6.06 5.52	5.97 3.50
Norm Flex Mod (Msi) CV	D 790	4.7 0.8	4.4 0.7
Norm Flexural Strength (ksi) CV	D 790	78.6 4.04	83.3 5.52
Norm $G_{12chord}$ (Msi) CV	D 3518	2.02 4.22	1.80 2.58
Norm Shear Stress (ksi) at 5% Strain CV	D 3518	8.03 8.50	8.27 3.80

5. Conclusions

It has been quantifiably demonstrated that the elevation of the resin feed source relative to the part can significantly affect the time it takes to infuse a part using VARTM. The presence of the resin distribution medium's effect on the infusion time has been examined quantitatively and qualitatively. It has also been shown that vacuum and resin source location affect resin infusion time and final part quality. Parts manufactured with either a single or double bag have a tendency to be thinner as the part approaches the location of the vacuum source.

The amount of consolidation pressure, as well as the method of applying pressure, has an effect on the final part geometry and V_f of a thick-section composite laminate. If thinner laminates with higher V_f are required for a given application, novel techniques of applying pressure and removing excess resin may be used to attain desired properties.

The goal is to remove as much of the labor and waste from the VARTM process as possible and provide a flexible, effective means for ensuring that the process produces the desired mechanical properties. To that end, using external visualization techniques coupled with embedded sensors provides a wealth of information hitherto unavailable from which to produce a closed loop process control system for VARTM manufacturing. The control system can be continuously expanded to include some of the effects studied in this report, including the adjustment of resin feed source, uniformity of consolidation, and the effect of locating and actuating both resin and vacuum sources.

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6. References

1. Williams, C., J. Summerscales, and S. Grove. "Resin Infusion Under Flexible Tooling (RIFT): A Review." *Composites Part A*, vol. 27A, pp. 517–524, 1996.

2. Steenkamer, D. A., V. M. Karbhari, D. J. Wilkins, and D. S. Kukich. "An Overview of the Resin Transfer Molding Process." CCM Report 94-02, University of Delaware, Newark, DE, 1994.

3. Abraham, D., S. Mathews, and R. McIlhagger. "A Comparison of Physical Properties of Glass Fibre Epoxy Composites Produced by Wet Lay-Up with Autoclave Consolidation and Resin Transfer Moulding." *Composites Part A*, vol. 29A, pp. 795–801, 1998.

4. Falzon, P. J., I. Herszenberg, and V. M. Karbhart. "Effects of Compaction on the Stiffness and Strength of Plain Weave Fabric RTM Composites." *Journal of Composite Materials*, vol. 30, no. 11, p. 1210, 1996.

5. Breiling, K. B., and D. O. Adams. "Effects of Layer Nesting on Compression-Loaded 2-D Woven Textile Composites." *Journal of Composite Materials*, vol. 30, no. 15, pp. 1710–1729, 1996.

6. Pearce, N., and J. Summerscales. "Compressibility of a Reinforcement Fabric." *Composites Manufacturing*, vol. 6, pp. 15–21, 1995.

7. Toll, S. "Packing Mechanics of Fiber Reinforcements." *Polymer Engineering and Science* [H. W. Wilson - AST], vol. 38, no. 8, pp.1337–1350, August 1998.

8. Pearce, N., F. Guild, and J. Summerscales. "An Investigation Into the Effects of Fabric Architecture on the Processing and Properties of Fibre Reinforced Composites Produced by Resin Transfer Moulding." *Composites Part A*, vol. 29A, pp. 19–27, 1998.

9. Seeman, W. H. "Plastic Transfer Molding Techniques for Production of Fiber Reinforced Plastic Structures." U.S. Patent No. 4,902,215, February 1990.

10. Saunders, R. A., C. Lekakou, and M. G. Bader. "Compression in the Processing of Polymer Composites Parts 1 and 2." *Composite Science and Technology*, vol. 59, 1999.

11. Luo, Y., and I. Verpoest. "Compressibility and Relaxation of a New Sandwich Textile Preform for Liquid Composite Moulding." *Polymer Composites*, vol. 20, no. 2, April 1999.

12. Sun, X., S. Li, and J. Lee. "Mold Filling Analysis in Vacuum Assisted Resin Transfer Molding. Part I: SCRIMP Based on a High-Permeable Medium." *Polymer Composites*, vol. 19, no. 6, December 1998.

13. Walsh, S. M. "In-Situ Sensor Method and Device." U.S. Patent No. 5,210,499, 1991.

14. Walsh, S. M., and R. V. Mohan. "Study of Staggered Flow Fronts With Applications to Sensor-Based Control." Proceedings of SPE ANTEC, 2681-2685, New York, NY, May 1999.

15. Owens Corning S-2 Glass® Product Information. Pub. No. 1-PL-14973-G, 1995.

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The continued growth of vacuum-based processes has warranted the development of both models and experimental studies designed to capture the unique aspects associated with this manufacturing technique. To that end, this report summarizes an initial set of experiments that characterize both the process and the resulting mechanical properties of components fabricated under a variety of process conditions. Specifically, resin flow studies are presented in part to demonstrate, the relative influence of key parameters on the flow front developed during impregnation. The effect of the distribution medium, which is used in a commercial version of VARTM known as Seeman's Composite Resin Infusion Molding Process (SCRIMP), is explicitly characterized. In addition, the variation of part thickness is also examined, and potential mechanisms responsible for these variations are presented. A battery of mechanical tests designed to correlate the effect of various processing conditions are also presented. A major finding is that thickness variation can be significant and, to some degree, random; also, precompaction of the preform significantly influences the amount of consolidation pressure needed during impregnation. Dimensional variations due to gradients in the pressure distribution of the vacuum affect permeability (and hence resin flow), as well as dimensional tolerances in manufactured parts.

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